Probing hadronization and jet substructure with leading particles in jet at H1

Mriganka Mouli Mondal, for the H1 Collaboration

CFNS, Stony Brook University

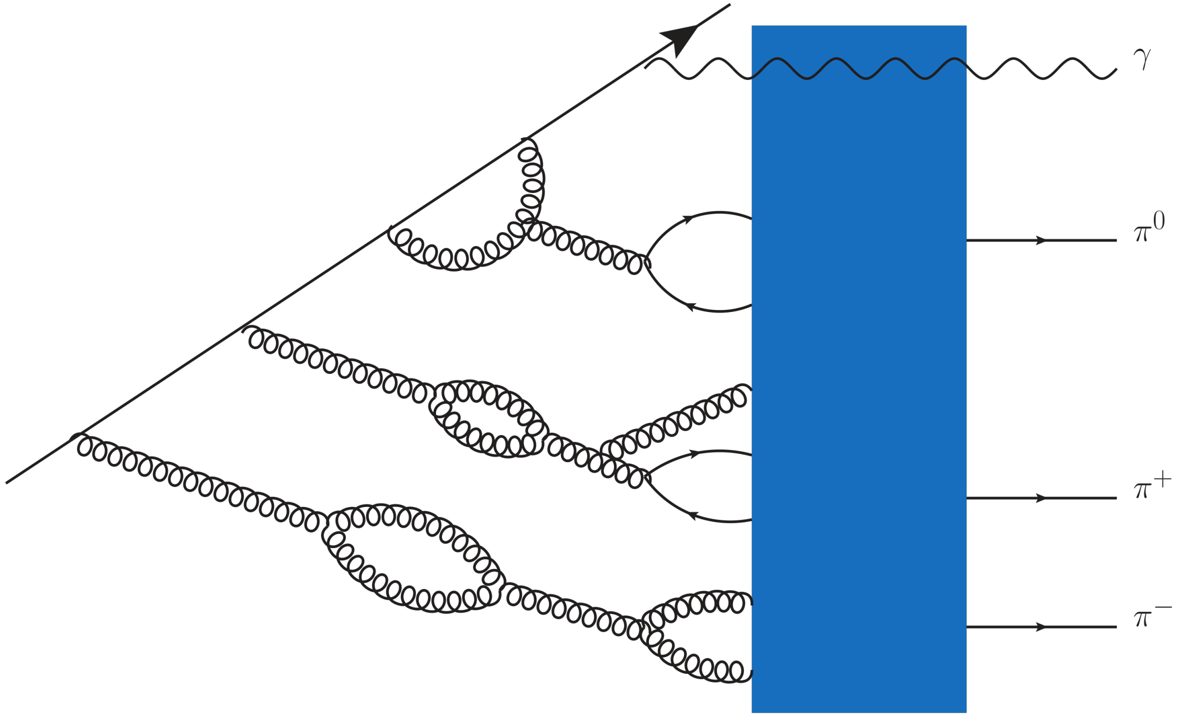
HERA4EIC Workshop, June 8, 2022

Outline

- **Observable** : charge-momentum correlation ($\boldsymbol{r_c}$) amongst leading hadrons in jets
- **Jet substructure :** partonic proxies in probing $\boldsymbol{r_c}$ at different splits (prongs)
- **Kinematic variables** : relative transverse momentum between leading particles/prongs (k_T) and formation time (t_{form})
- **H1 Measurements**
  - Jets at H1 and leading particles & prong kinematics
  - Prong and its correlation with leading particles
  - $\boldsymbol{r_c}$ with k_T, t_{form} and jet-p_T
- **Summary**

Leading particles in jets

Parton shower evolution +
nonperturbative gluon splitting



Hadronization
(nonperturbative)

Jets are collimated streams of particles

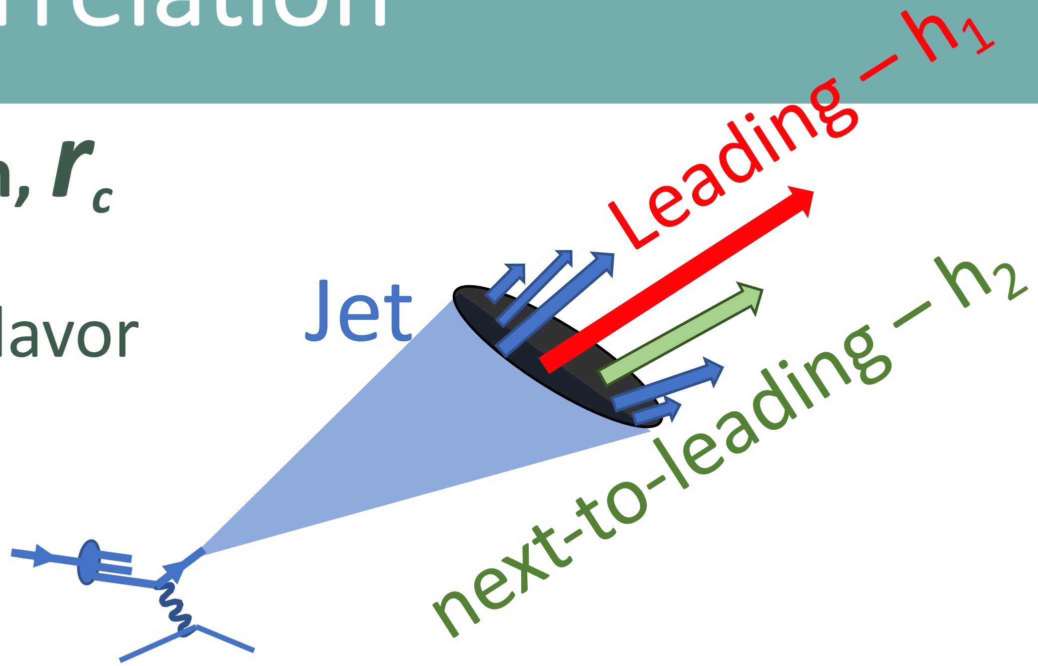
Dynamics of hadronization can be studied through correlations among particles in a jet

Leading and next-to-leading particles : nonperturbative in origin

charge-energy correlation

Observable : charge-momentum correlation, r_c

- Correlations in momentum, charge and flavor
- **Leading(L)** and **next-to-leading (NL)** momentum particles in a jet
- h1 and h2 are charged hadrons only



$$\boxed{r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}}$$

N_{CC} : # Jets where L and NL particles have same sign charges

$N_{C\bar{C}}$: # Jets where L and NL particles have opposite sign charges

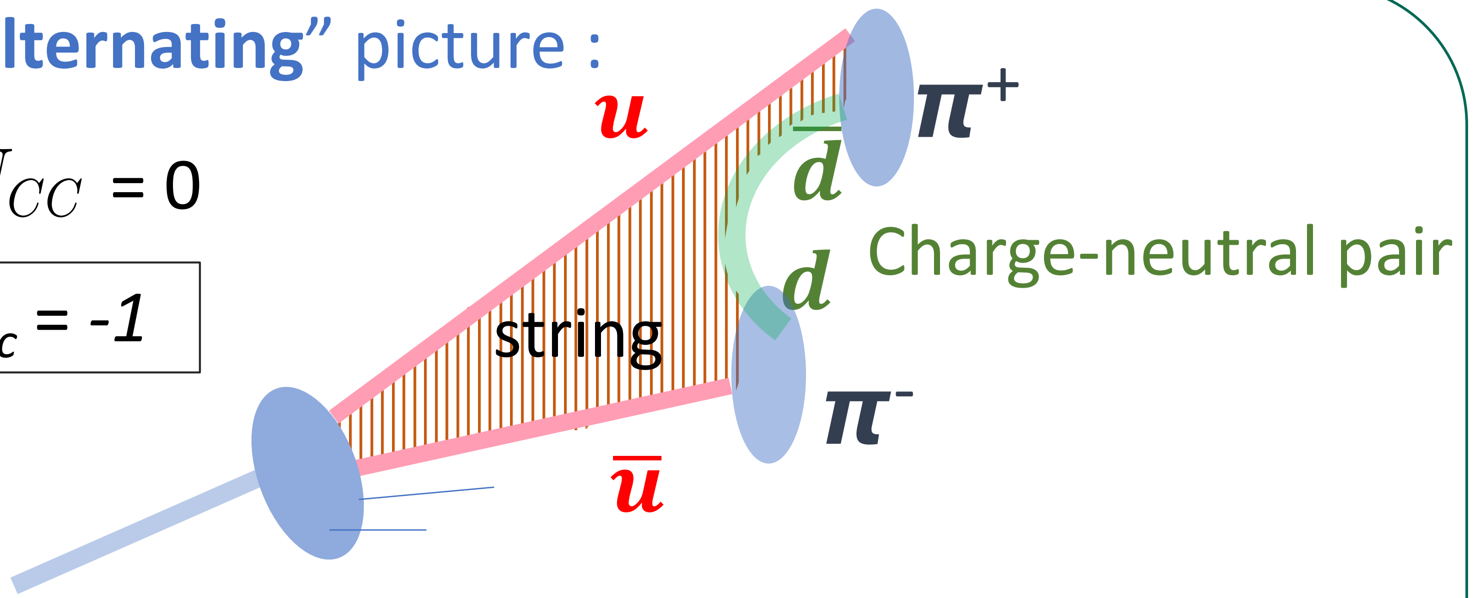
Phys. Rev. D **105**, L051502, Y-T. Chien, A. Deshpande, M. M. Mondal, and G. Sterman

Significance of r_c

"**alternating**" picture :

N_{CC} = 0

$\boxed{r_c = -1}$



Partonic final state : u and $\bar{u}$

Combine charge-neutral pair : $\bar{d}$ and d

"**random**" picture :

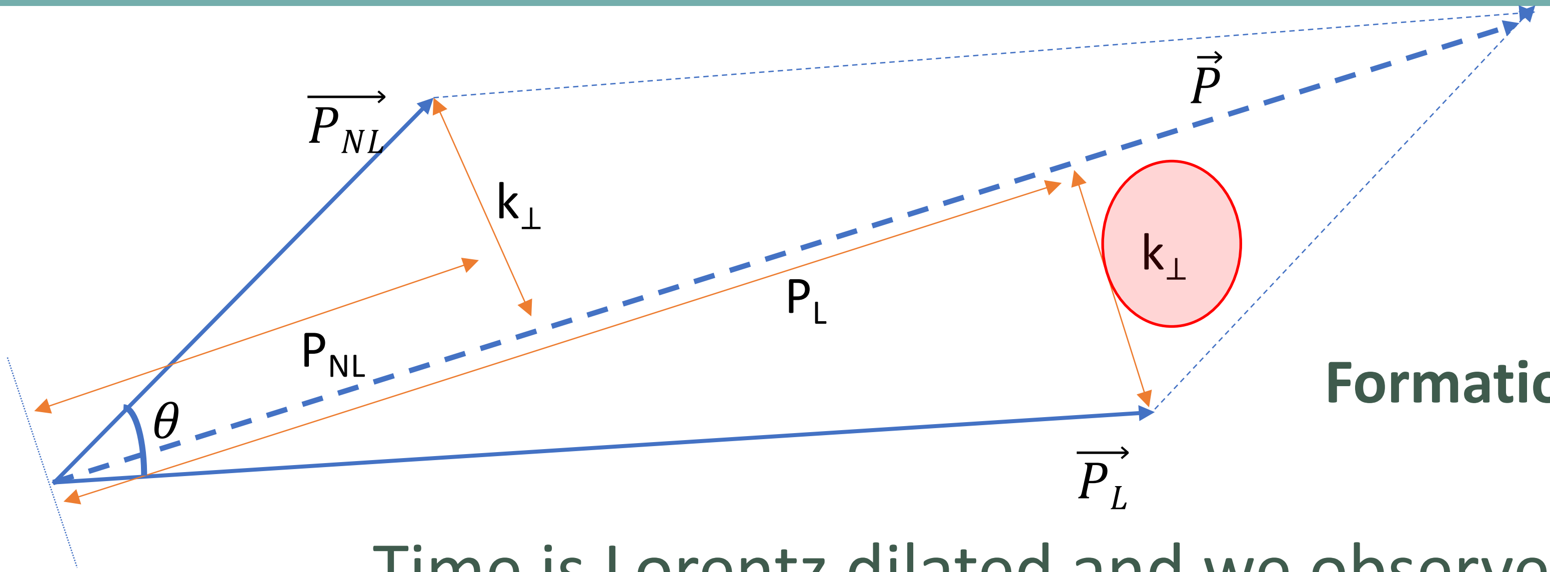
no charge correlation

N_{CC} = $N_{C\bar{C}}$

$\boxed{r_c = 0}$

r_c is a measure of the fraction of "string-like hadronization"

Formation time



$z = P_{NL}/(P_{NL}+P_L)$
$P_L = (1\text{-}z)P$
$P_{NL} = zP$

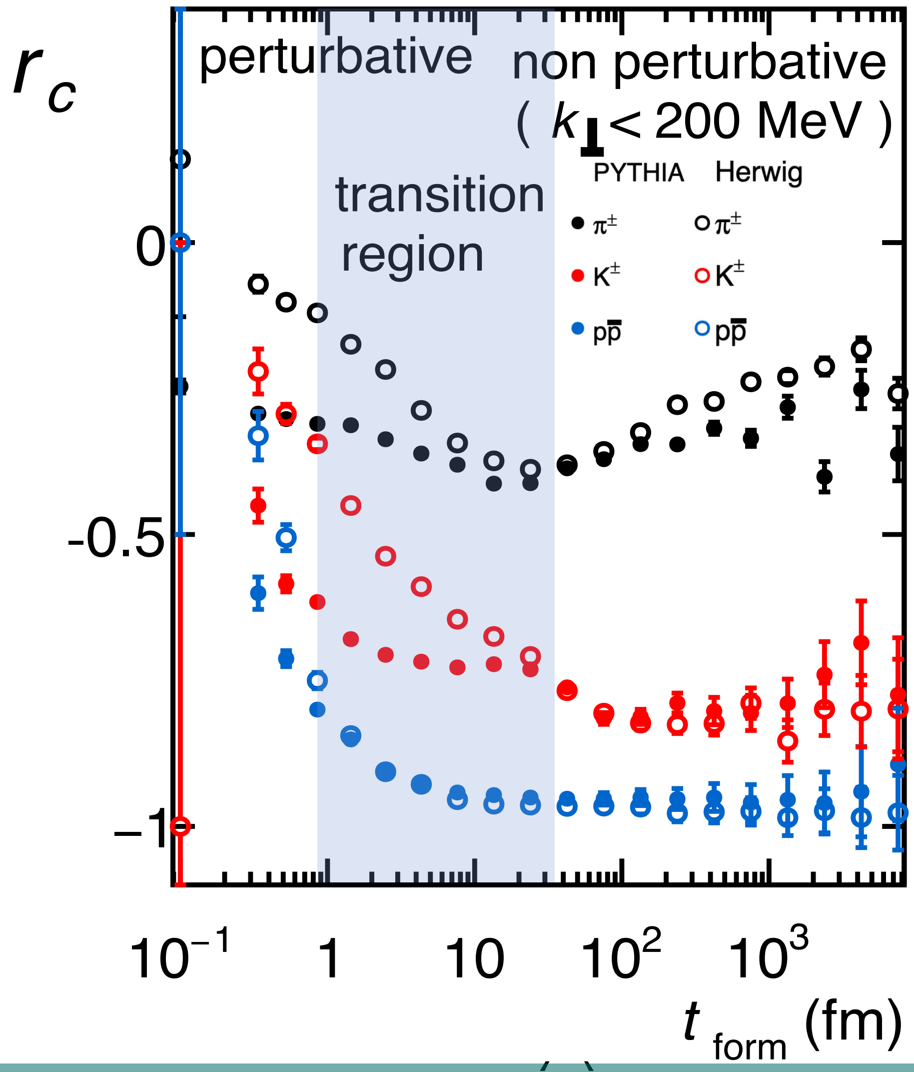
Formation time, t_{form} = [2z(1-z) P] / k_{perp}^2

Time is Lorentz dilated and we observe in lab frame

- ✓ **Perturbative (t_{form} < ~1fm)**
  L and NL particles seem to separate after a very short time, which might decorrelate their hadronization
- ✓ **Nonperturbative (t_{form} > ~10 fm)**
  nonperturbative transverse momenta in the jet, $k_\perp$ < 200 MeV.
  Going to longer t_{form} or smaller $k_\perp$ leads to no new dynamics

Measurement of r_c

Phys. Rev. D **105**, L051502



- At early time de-correlations for wide-angle, perturbative emissions.
- There is strong flavor dependence in r_c

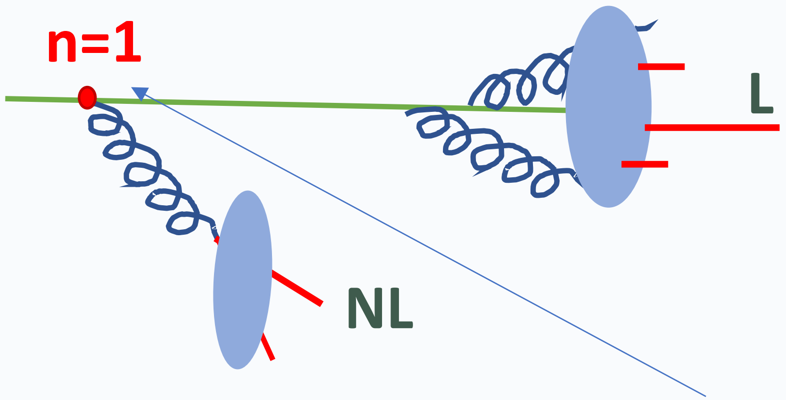
Where to measure

✓ Need particle Identifications at very high momentum to measure falvor correlations at **EIC (flavor),** Belle (flavor)

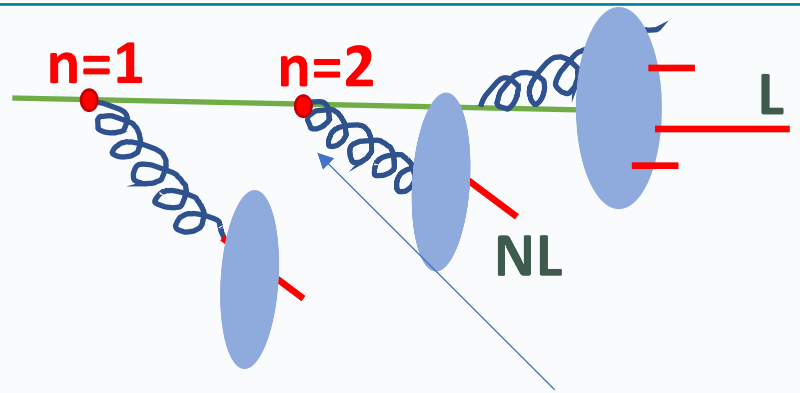
✓ Charge correlations at : LEP, **H1**, RHIC, LHC

This would be the first measurement on r_c for leading charge particles

r_c with subjets



L and NL particle get **resolved in first prong (n_R = 1)**



L and NL particle get **resolved in the second prong (n_R = 2)**

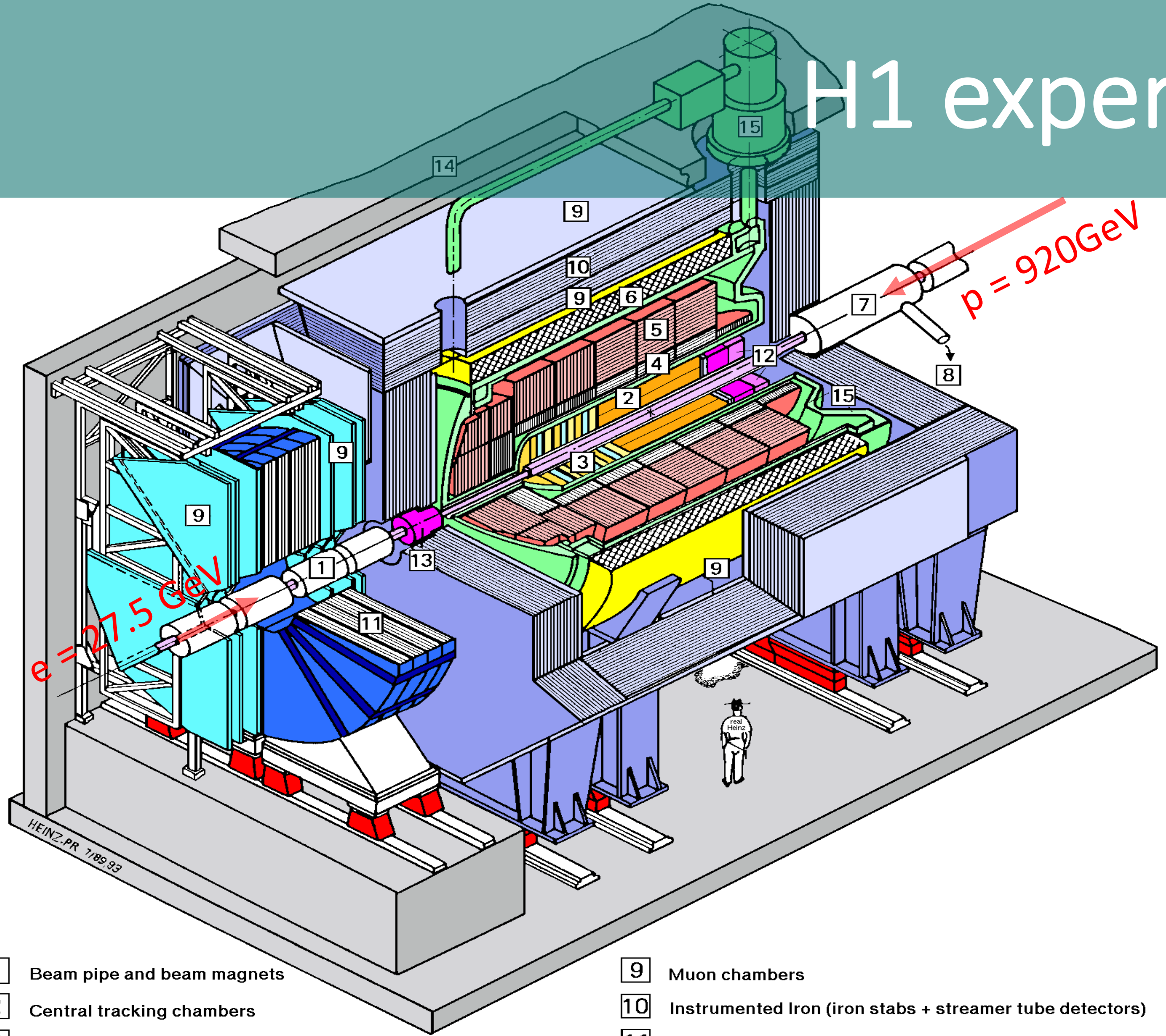
- L, NL particles are strongly correlated with the hardest patron
- Prong structure represent the partonic proxy
- Charge of a subjet is the charge of its leading particle

Using Recursive soft drop - JHEP06(2018)093

$$z_{12} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta} , \qquad z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

- Anti-kt R=1.0 and C/A de-clustering tree
- following hardest branch
- dynamic radius

H1 experiment



1 Beam pipe and beam magnets
2 Central tracking chambers
3 Forward tracking and Transition radiators
4 Electromagnetic Calorimeter (lead) } Liquid Argon
5 Hadronic Calorimeter (stainless steel) } Liquid Argon
6 Superconducting coil (1.2T)
7 Compensating magnet
8 Helium cryogenics
9 Muon chambers
10 Instrumented Iron (iron stabs + streamer tube detectors)
11 Muon toroid magnet
12 Warm electromagnetic calorimeter
13 Plug calorimeter (Cu, Si)
14 Concrete shielding
15 Liquid Argon cryostat

Liquid Ar Calorimeter

$\boldsymbol{\sigma}/E \approx 11\%/\sqrt{E_{e.}} \oplus 1\%$ (electromagnetic)

$\boldsymbol{\sigma}/E \approx 50\%/\sqrt{E_h} \oplus 3\%$ (hadronic)

CTD

Single Track resolution

$\sigma p_T / p_T = 0.2\%\ p_T/\mathrm{GeV} \oplus 1.5\%$

$\boldsymbol{\sigma}_\theta = 1$ mr

(magnetic field = 1.16 T)

Data : 2004-2007

$\sqrt{s} = 319$ GeV, $\mathcal{L} = 361\ \mathrm{pb}^{-1}$

Event selection and Jet reconstruction

Technical cuts :

-30 cm < zVertex < 30 cm

45 GeV< E-pz < 65 GeV

DIS kinematics :

$Q^2 > 150\ \mathrm{GeV}^2$

0.2< y < 0.7

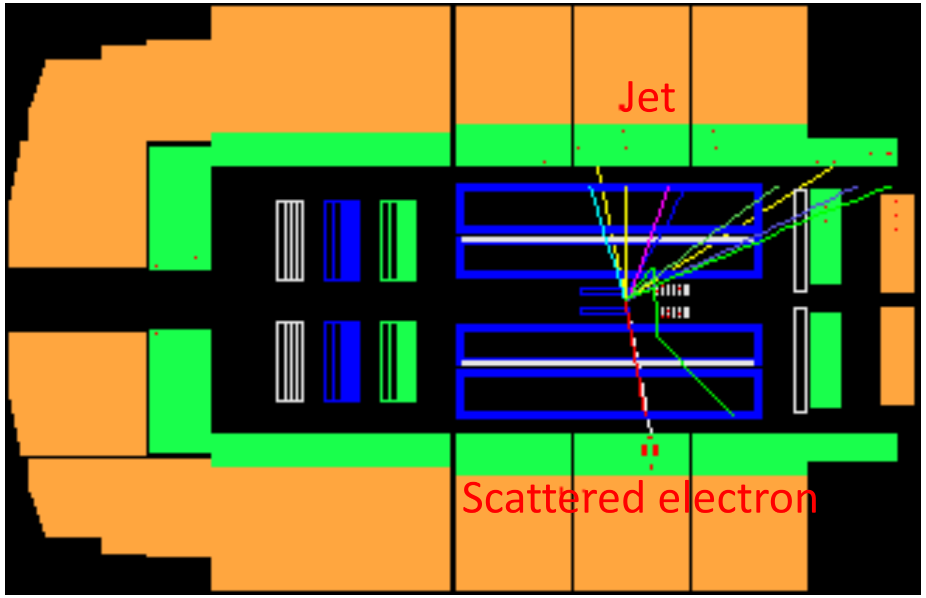
Jet Reconstructions : (Lab frame)

Tracks and clusters : $p_T > 0.2$ GeV/c

anti-kt R = 1.0

$p_{T,Jet} > 5.0$ GeV/c

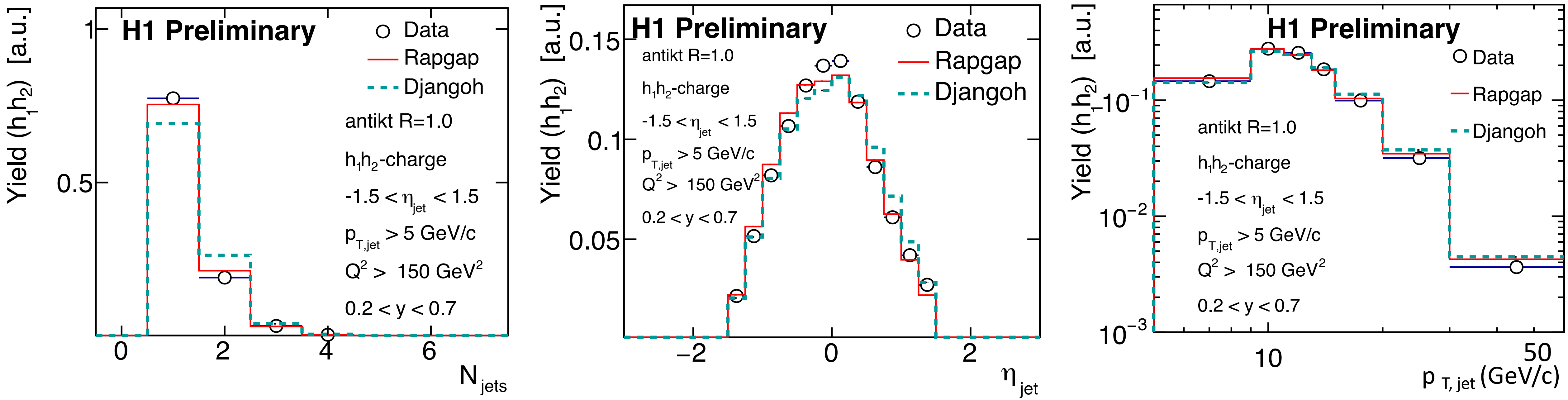
$-1.5 < \eta_{T,Jet} < 1.5$



- ✓ The leading and next-to-leading constituents of the jet are selected by their momentum along the jet axis.
- ✓ Both the leading and the next-to-leading constituents are required to be charged (CTD track)

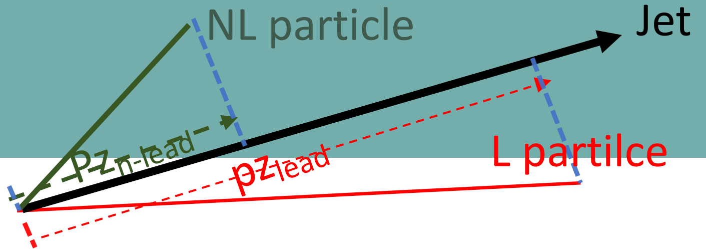
Reconstructed Jets

anti-kt R = 1.0 , $p_{T,Jet}$ > 5.0 GeV/c , -1.5 < $\eta_{T,Jet}$ < 1.5 and L,NL charge tracks (Only the leading p_T jet is used for the analysis)

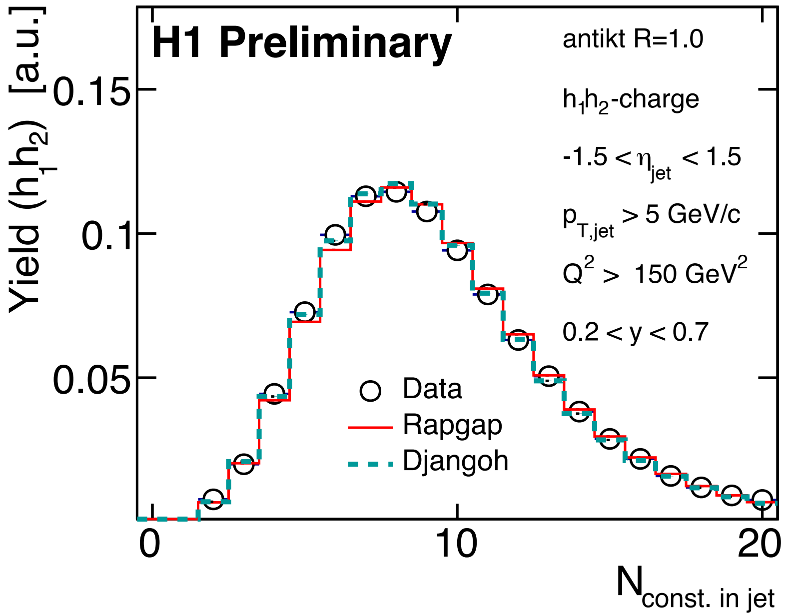


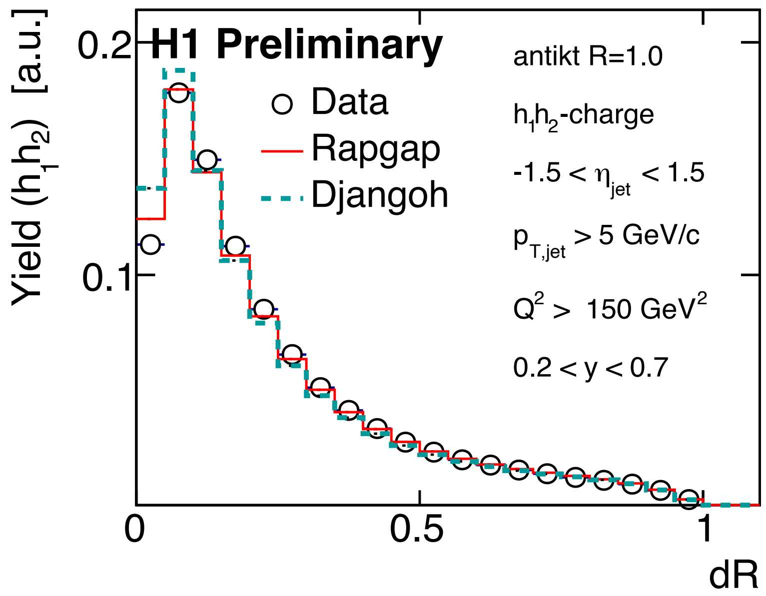
- ✓ Djangoh : Color Dipole Model + Lund string fragmentation and QED radiative corrections
- ✓ Rapgap : QCD matrix elements DGLAP based; with strongly ordered transverse momentum of subsequently emitted partons, + Hadronization : Lund string fragmentation like Pythia and QED radiations
- ✓ Djangoh and Rapgap reproduce the DATA distributions well (reconstruction level)

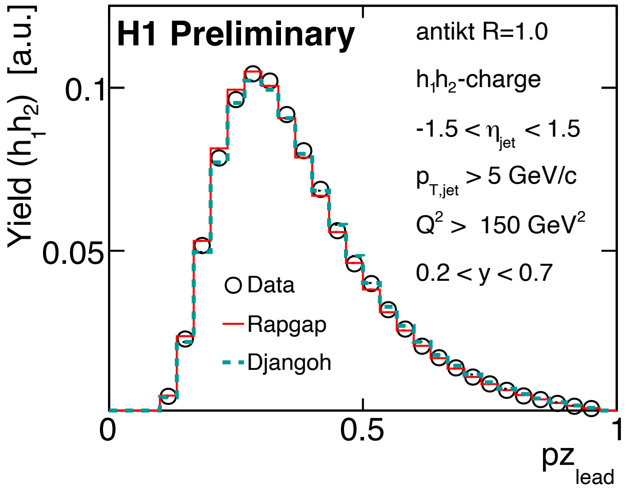
Constituents in Jet

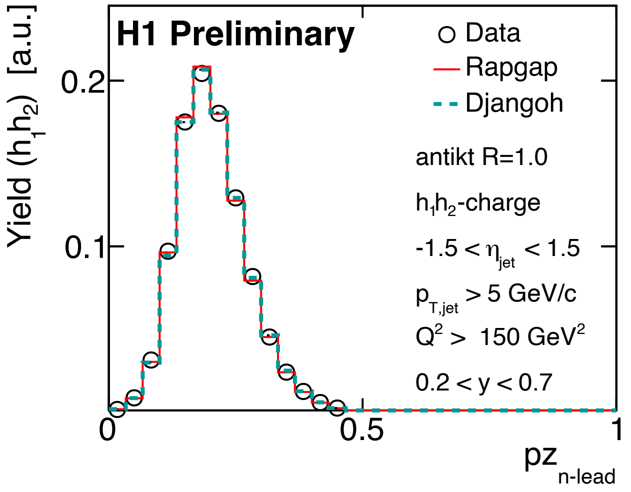


anti-kt R = 1.0 , $p_{T,Jet}$ > 5.0 GeV/c , -1.5 < $\eta_{T,Jet}$ < 1.5 and L,NL charge tracks



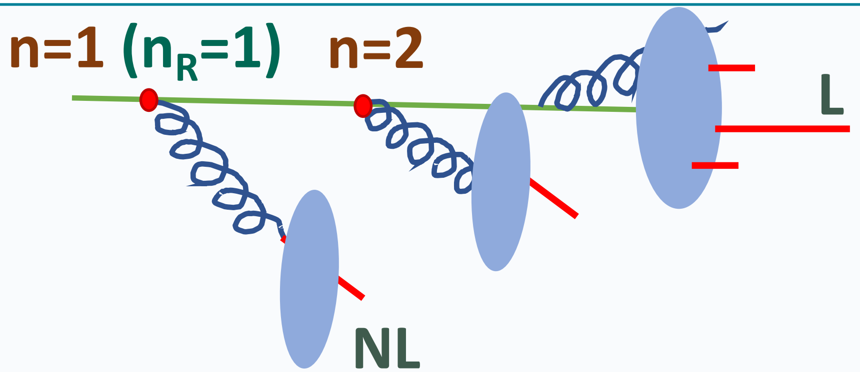




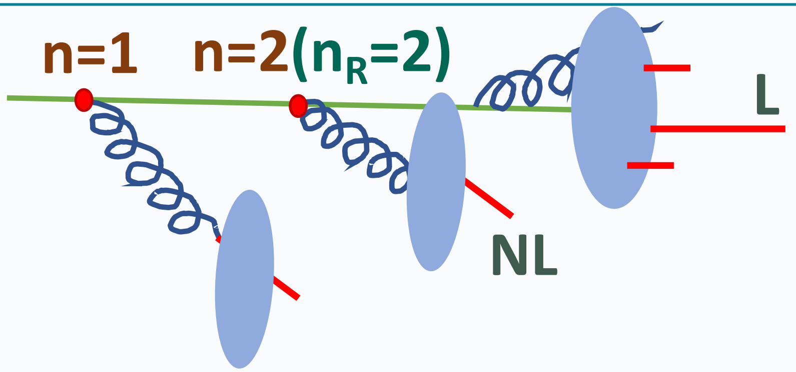


- ✓ Required two leading particles in jets to be charged
- ✓ Djangoh and Rapgap reproduce the DATA distributions well

Measurement of r_c at different prongs



L and NL particle get **resolved** in first prong (n_R = 1)

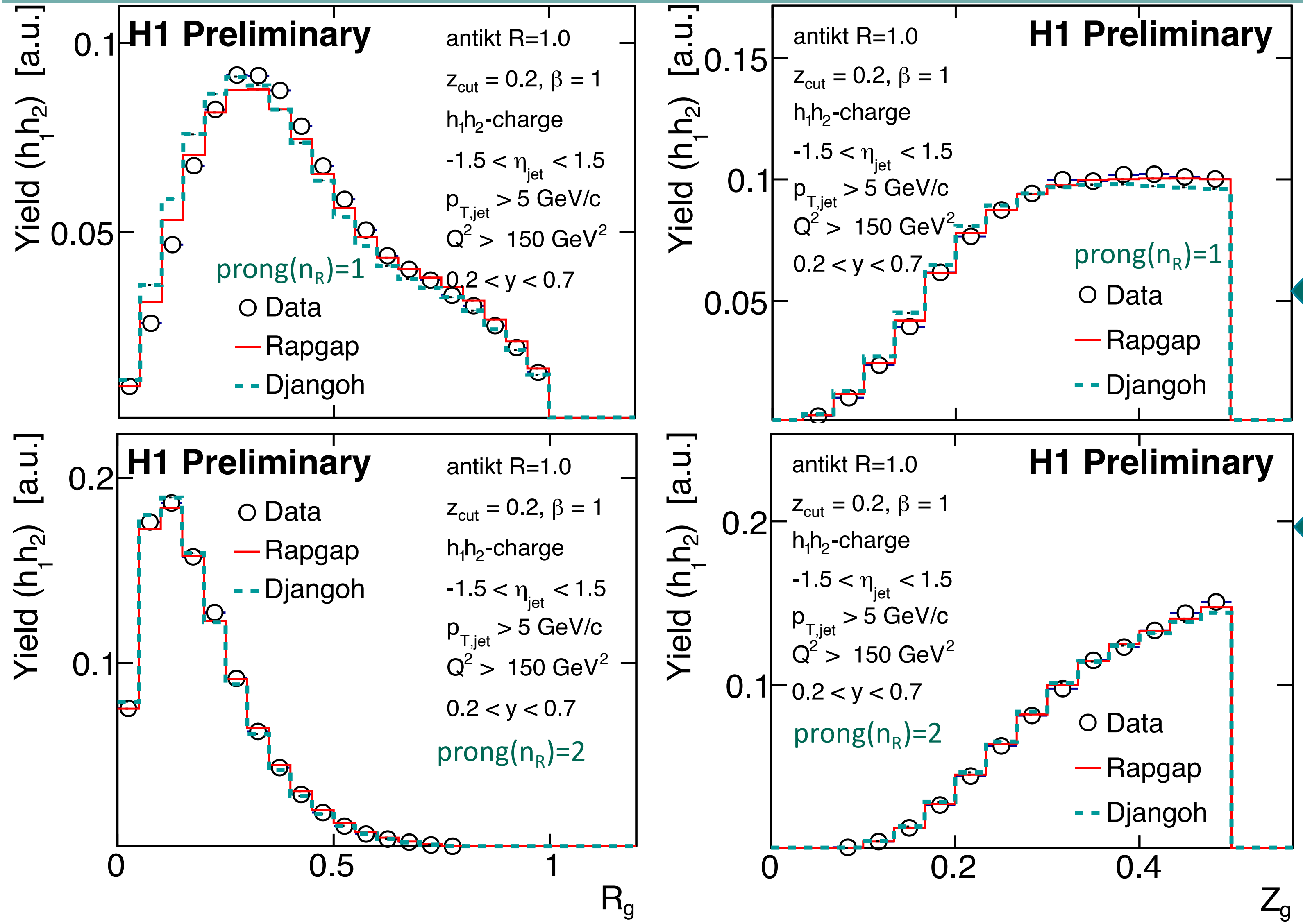


L and NL particle get **resolved** in the second prong (n_R = 2)

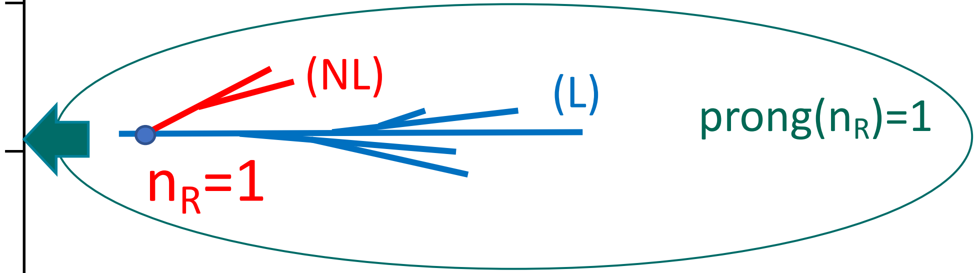
We will measure

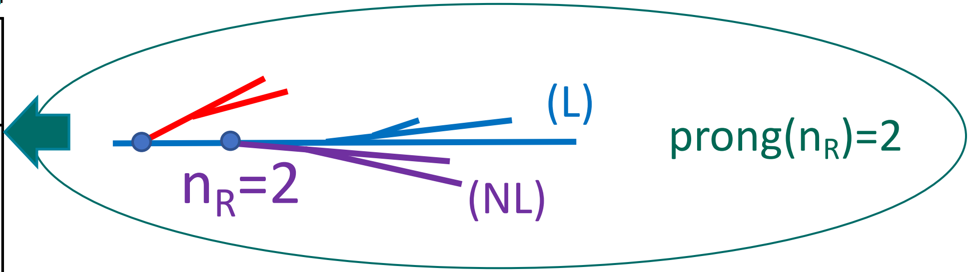
- ✓ r_c for L and NL particles
- ✓ r_c for n_R=1. (1st prong)
- ✓ r_c for n_R=2, n_R=3, n_R=4, ……. (2nd+ prong)

Prong R_g and Z_g distributions



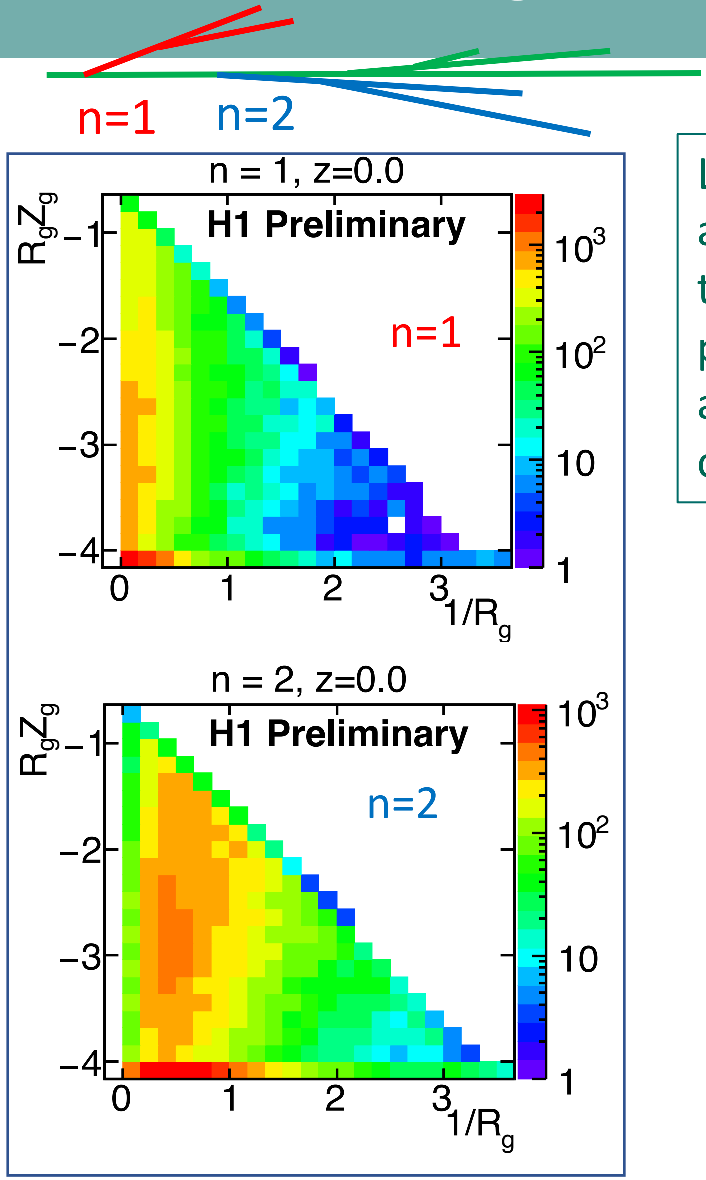
$$z_{12} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}, \qquad z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$





✓ R_g of the 1st split is wider and relatively carrying small Z_g compared to the 2nd+ splits

Correlating L &NL particles with prongs in Lund plane



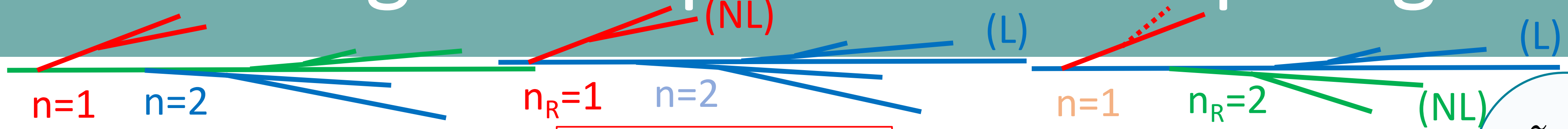
Leading and next-to leading particles are not correlated

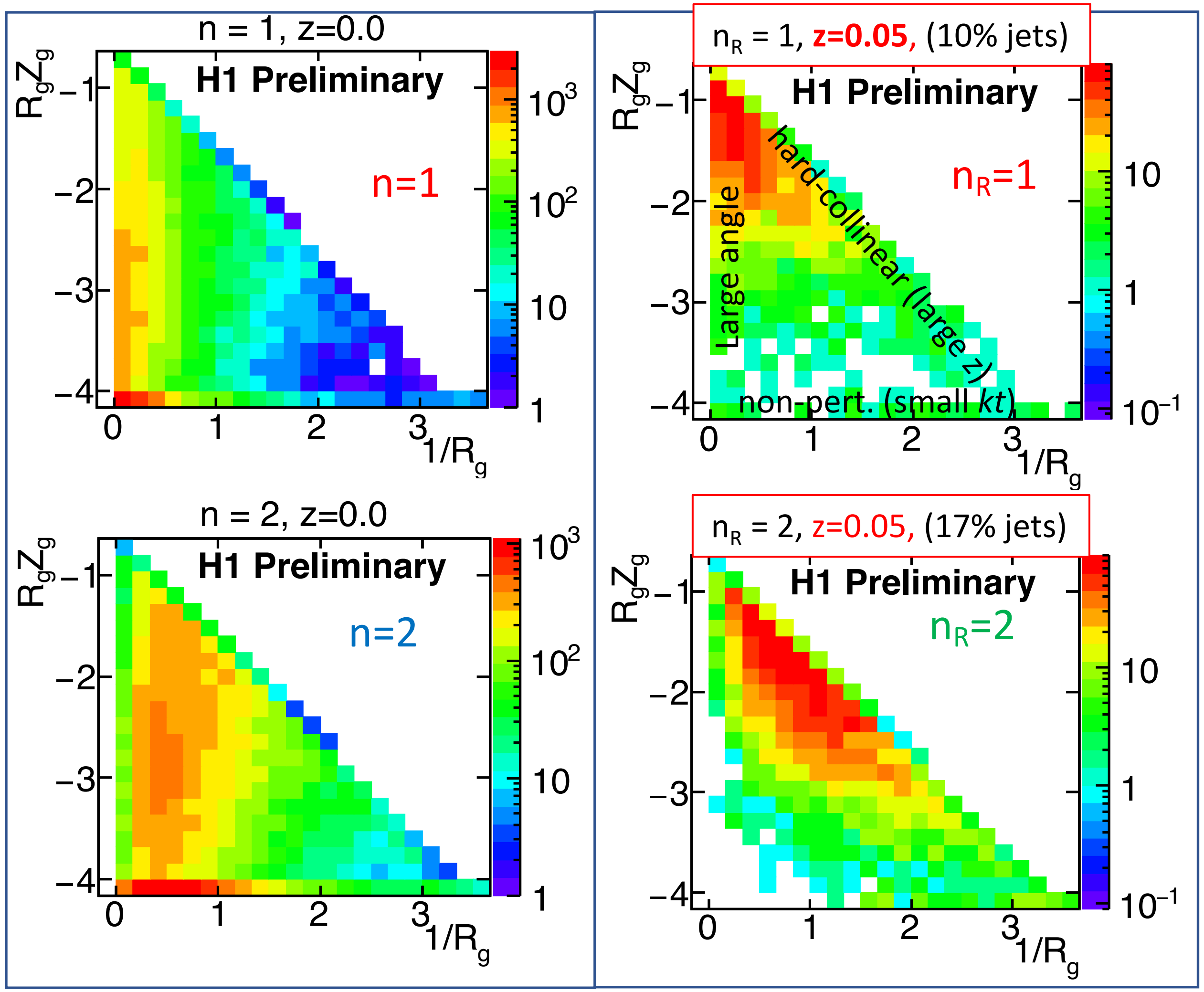
$$z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

$$z_{12} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

First split with small z_{cut} = 0 are large angle soft radiations

Correlating L &NL particles with prongs in Lund plane





Leading and next-to leading particles are correlated

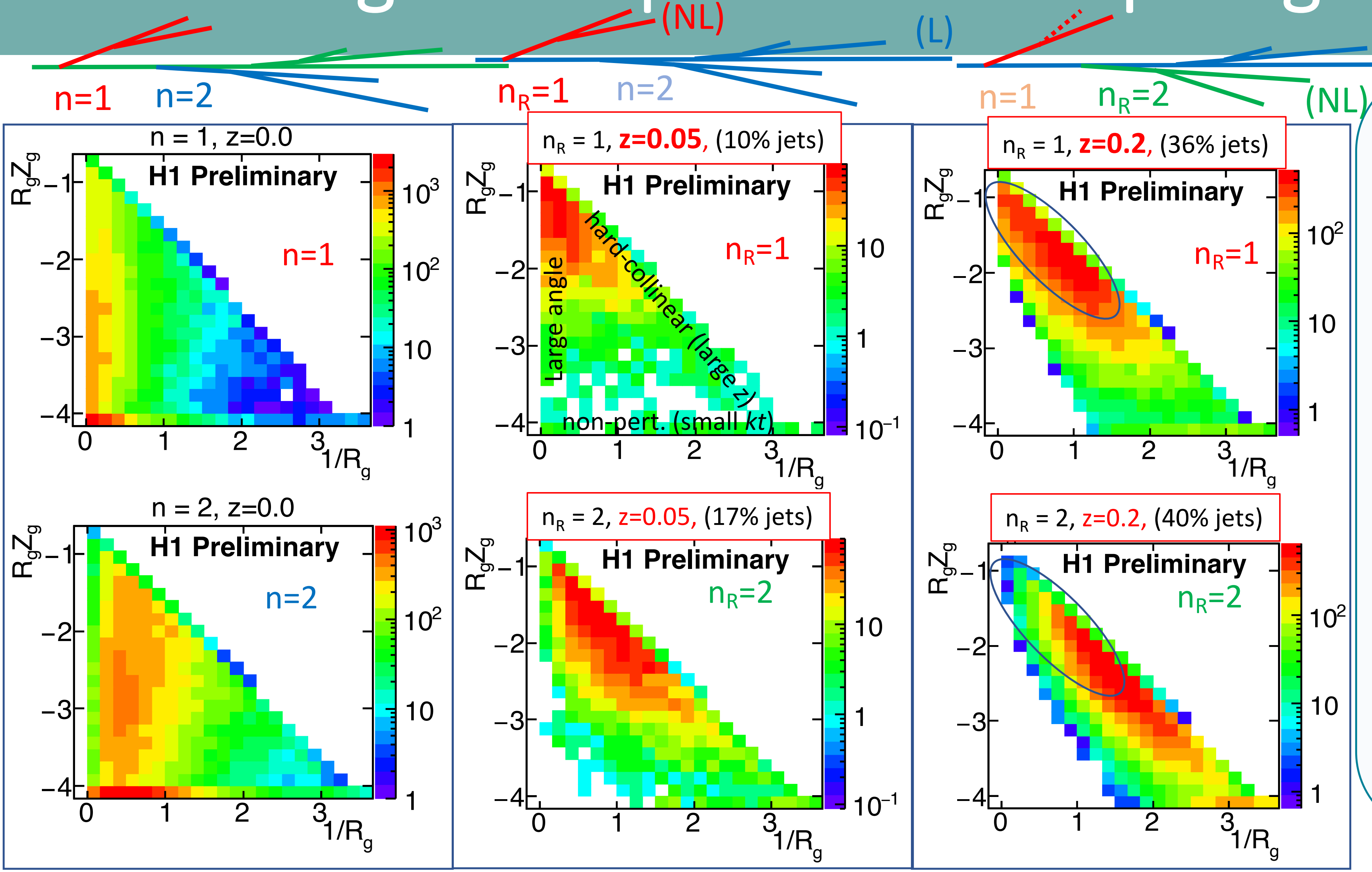
$$z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

$$z_{12} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

First split with small z_{cut} = 0 are large angle soft radiations

Small fraction of n=1 is in the n$_R$=1 class

Correlating L &NL particles with prongs in Lund plane



$$z_{12} \equiv \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$

$$z_{12} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

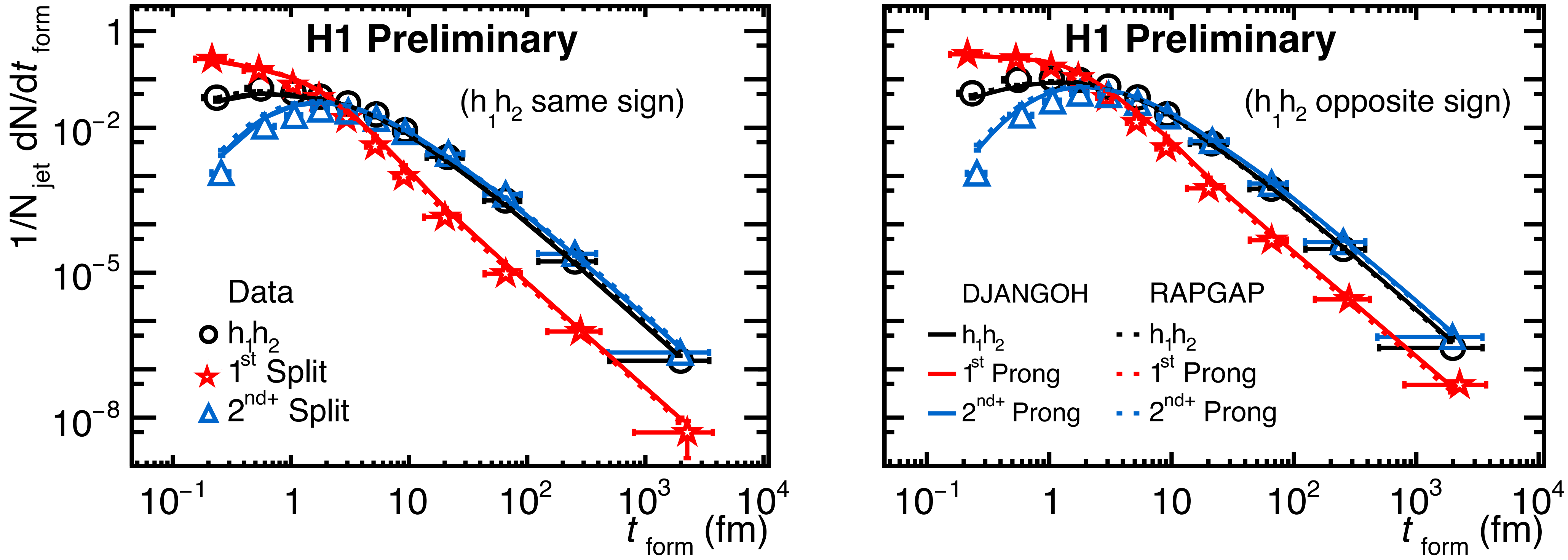
First split with small z_{cut} = 0 are large angle soft radiations

Small fraction of n=1 is in the n_R=1 class

z_{cut} = 0.2 redistribute between n_R=1 class and n_R=2+ classes so that n_R=1 would have sufficient events which are relatively wider angle radiations.

r_c with formation time, $k_\perp$, $p_{T,jet}$

formation time distributions

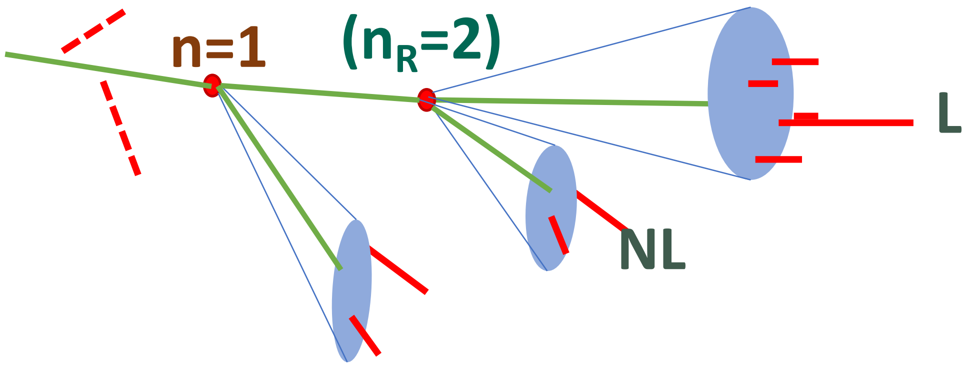


✓ Density of leading pairs in small formation time is much large in the 1^{st} split compared to that of later splits.

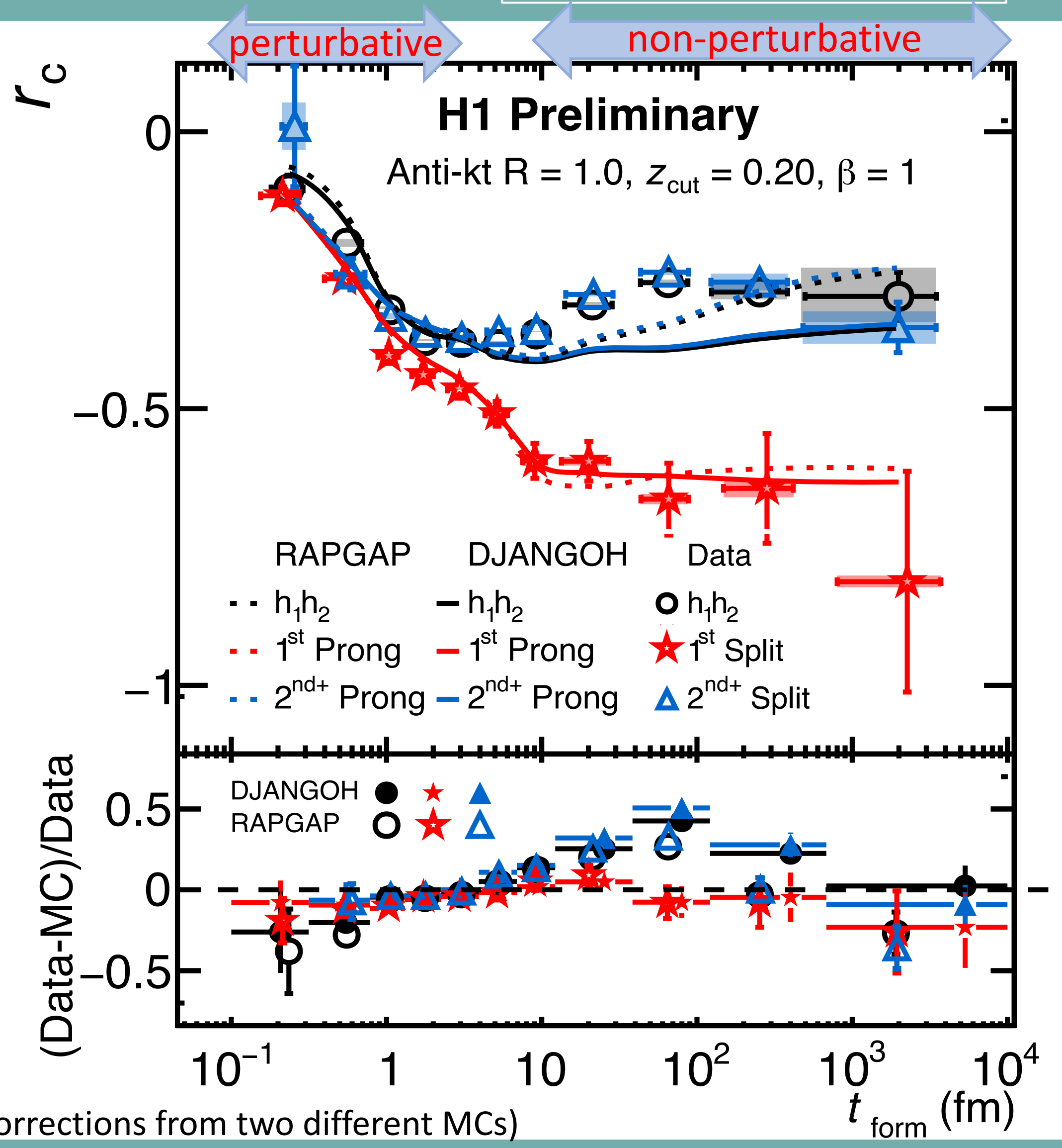
r_c with formation time

$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$

- ✓ Large decorrelations is seen in $\boldsymbol{r_c}$ at small formation time (< 1 fm)
- ✓ At large formation time $\boldsymbol{r_c}$ is stronger for 2^{nd+} splits compared to that of 1^{st} split
- ✓ Rapgap and Djangoh values are comparable to data

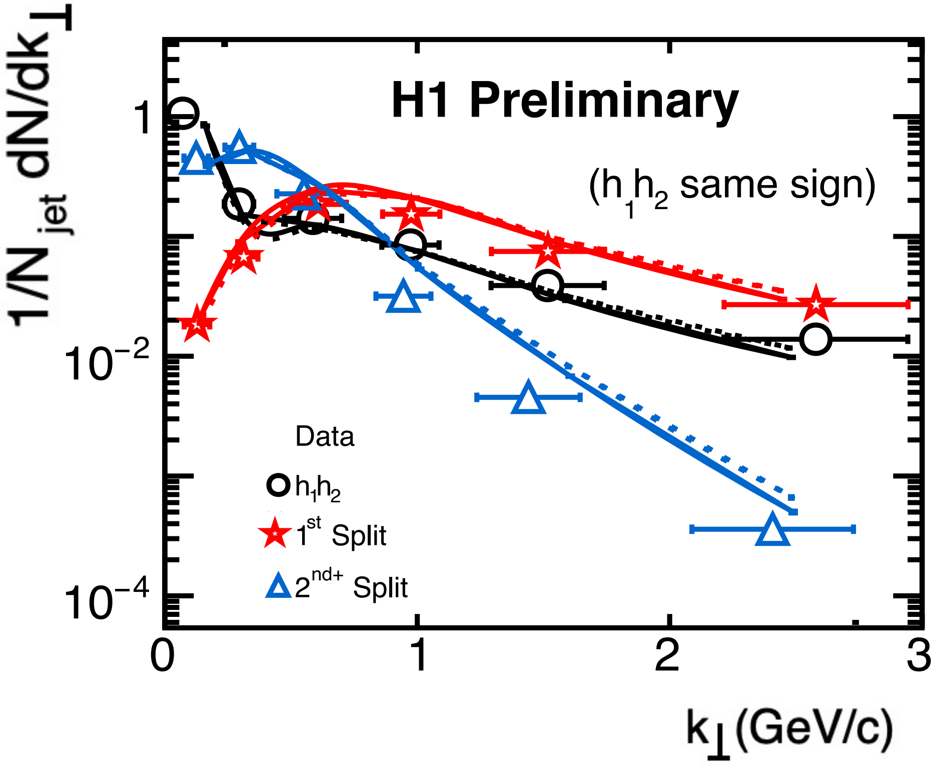


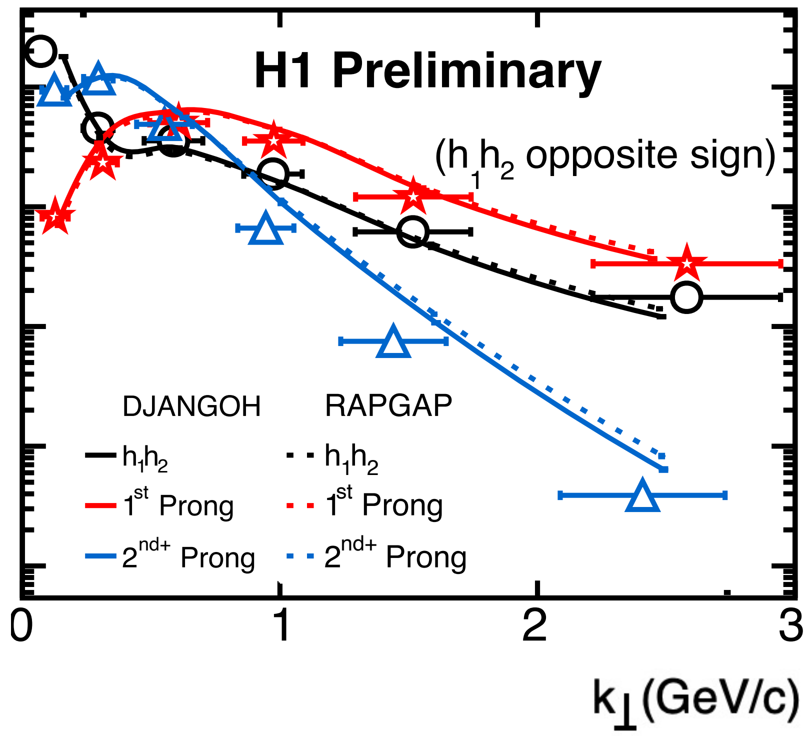
L NL particles are surrounded by perturbative emissions



(Error band : bin-by-bin corrections from two different MCs)

$k_\perp$ distributions



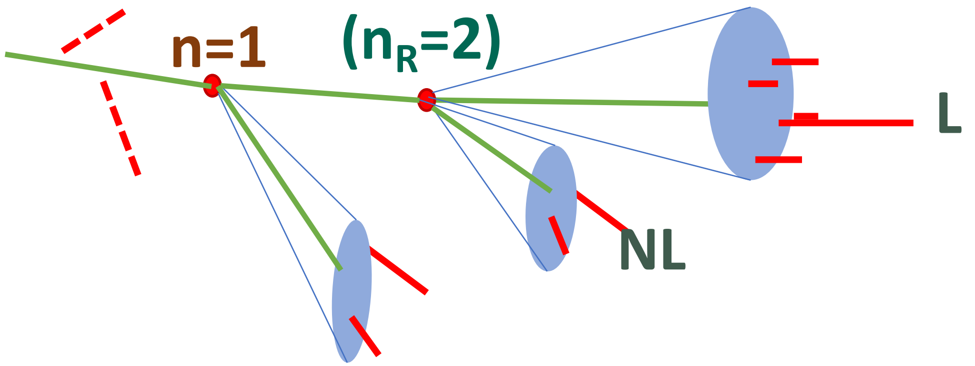


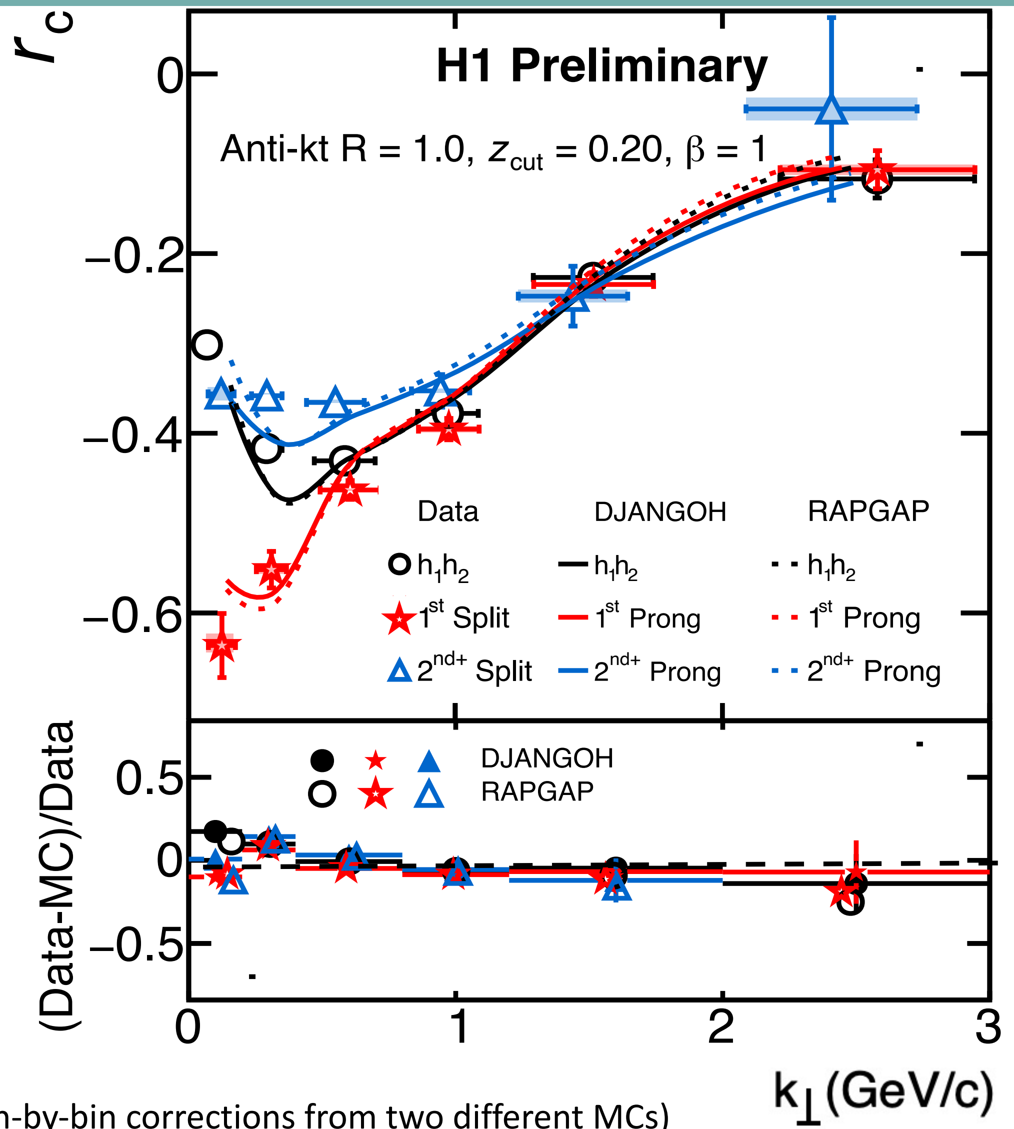
✓ 1^{st} split mean value is large $k_\perp$ compared to 2^{nd+} splits

r_c with $k_\perp$

$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$

- ✓ Small $k_\perp$ belong mostly in nonperturbative domain and r_c is large. Large $k_\perp$ are related mostly to early gluon splits and r_c is approaching to zero
- ✓ Small $k_\perp$ corresponds to large formation time and stronger correlation observed in the 1st split

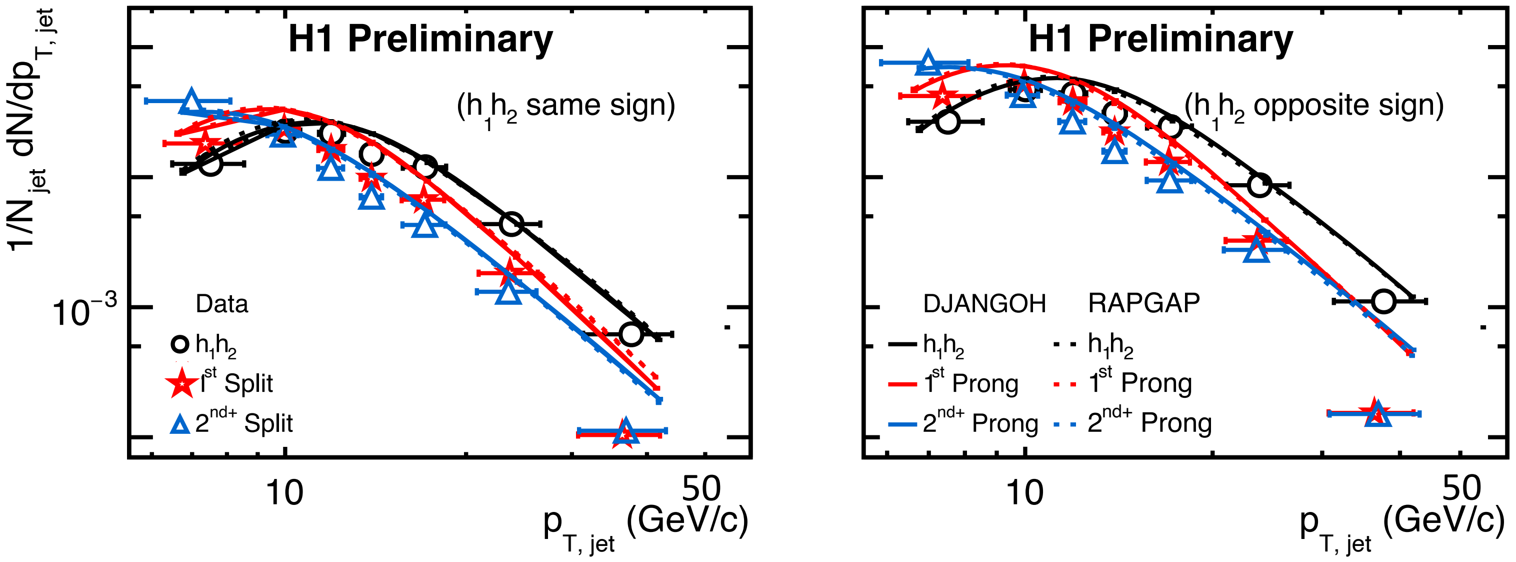


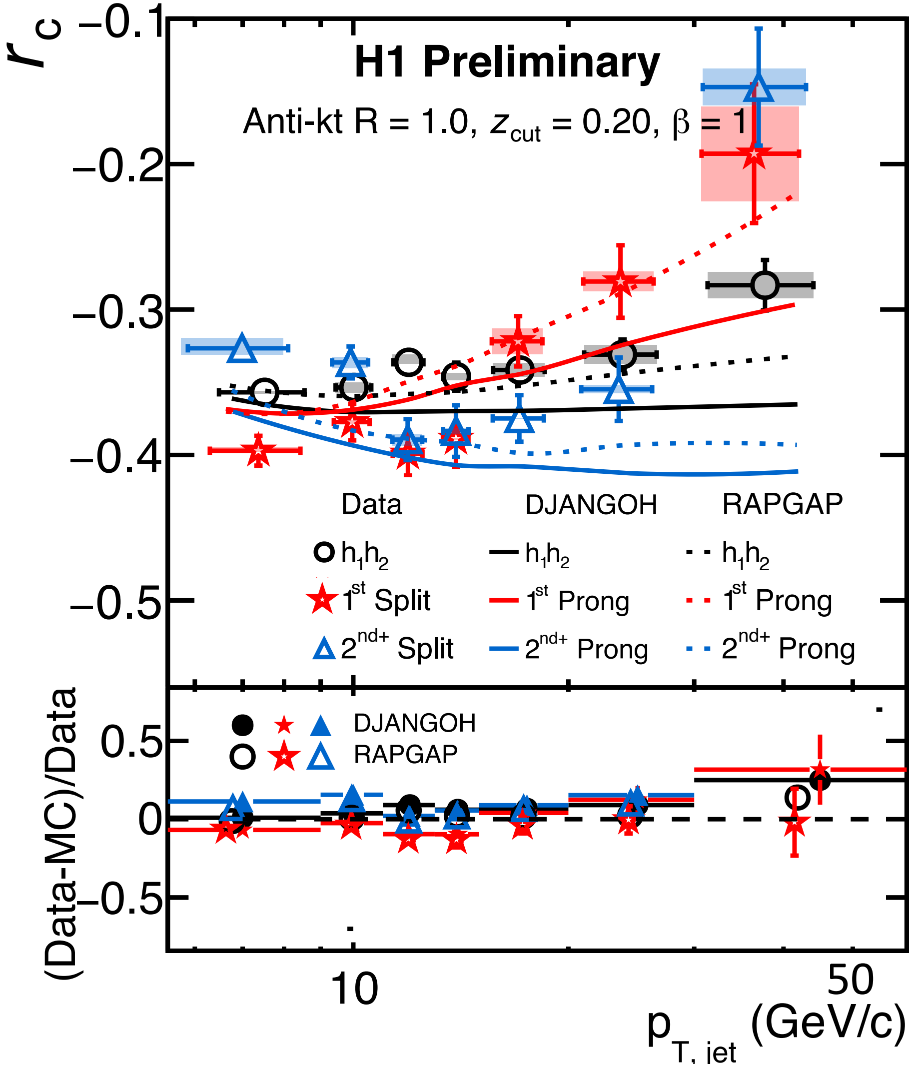


(Error band : bin-by-bin corrections from two different MCs)

r_c with $p_{T,jet}$

$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$





(Error band : bin-by-bin corrections from two different MCs)

✓ We see a slow decorrelations in r_c with jet transverse momentum.

Summary

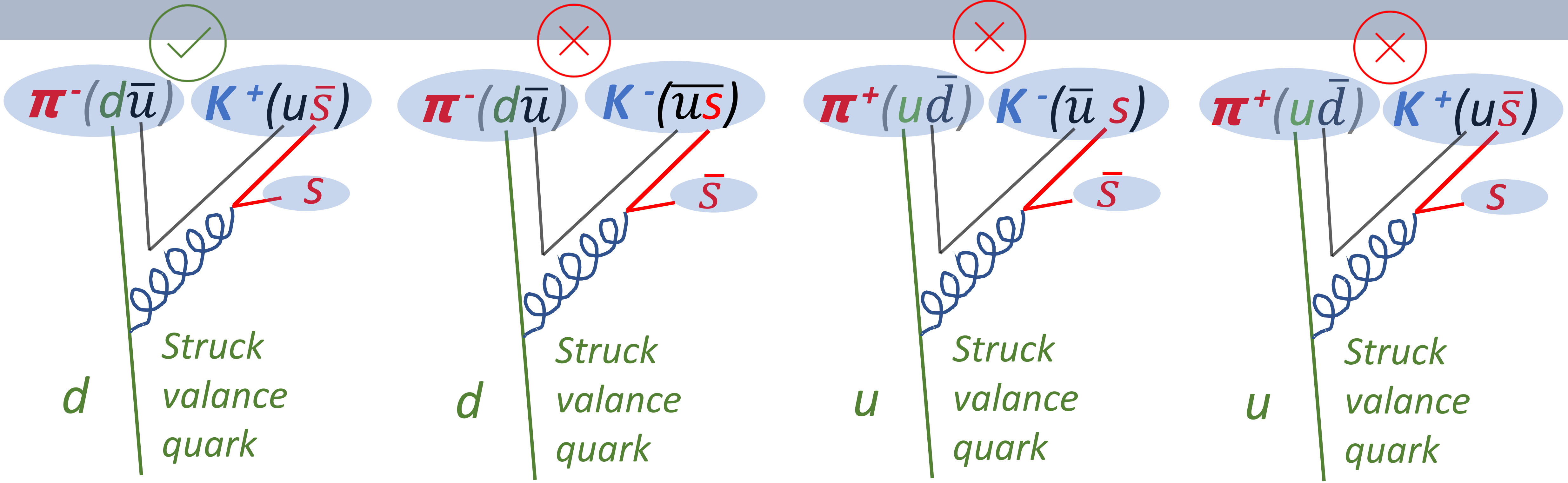
- Fragmentation in Jets using leading particles in them is studied employing the H1 detector.
- This is the first measurement of the observable $\boldsymbol{r_c}$. Dependency of $\boldsymbol{r_c}$ measured in formation time, $k_\perp$ and jet transverse momentum.
- r_c is measured from subjets obtained from recursive soft drop and in correlations with leading particles.
- The charge correlations with leading particles in prongs are sensitive to the level of split. We see r_c is small in the perturbative region and large in nonperturbative region.
- Rapgap and Djangoh follow the trend to the data and correlations are comparable.

- EIC would be promising in measuring such correlations for various flavor combinations

backup

Flavor correlations

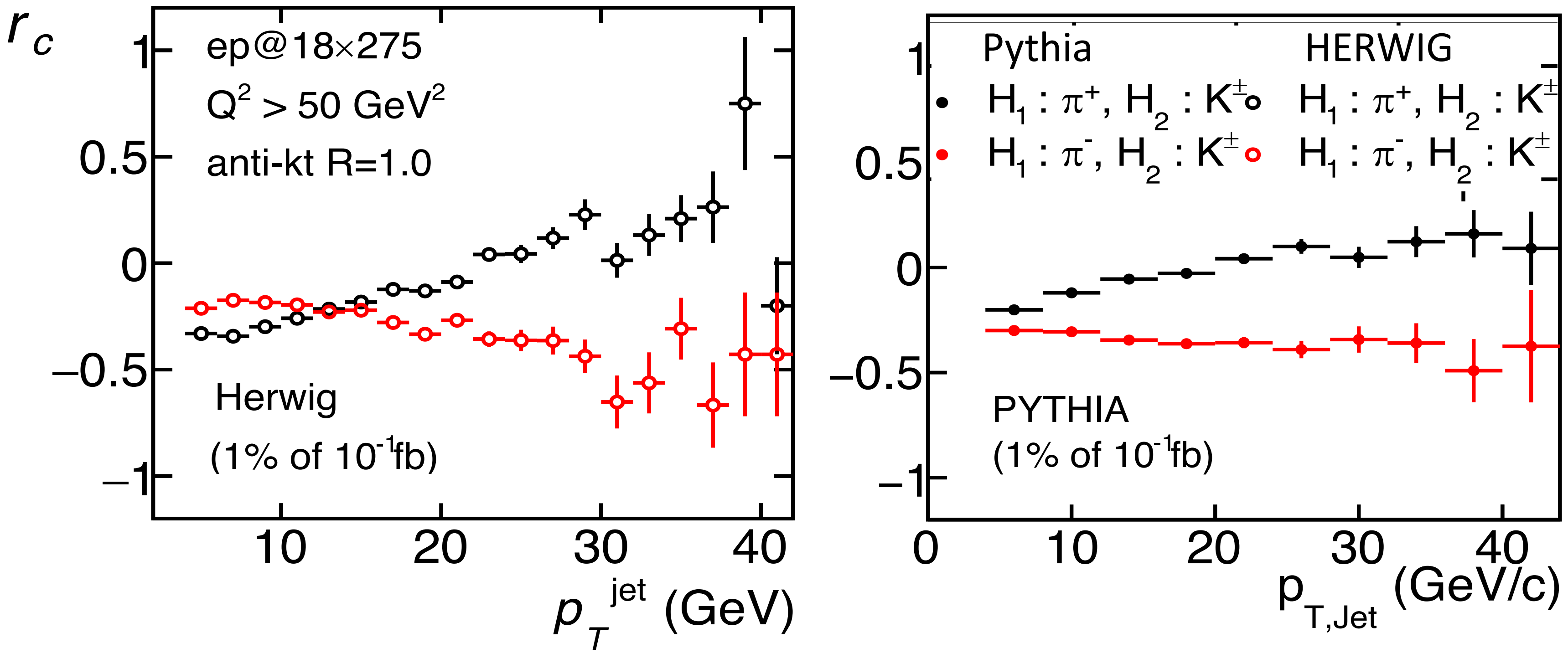
$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$



With struck valance quark, L(π^-) NL(K^+) is preferable for the simplest string breaking between L and NL particles

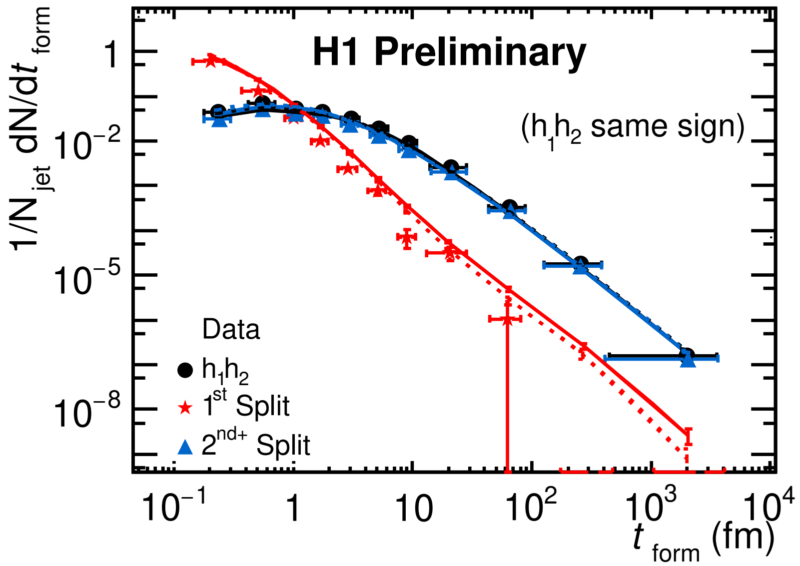
- From this naive picture one expects r_c for $\pi^-K^\pm$ to be stronger than that of $\pi^+K^\pm$

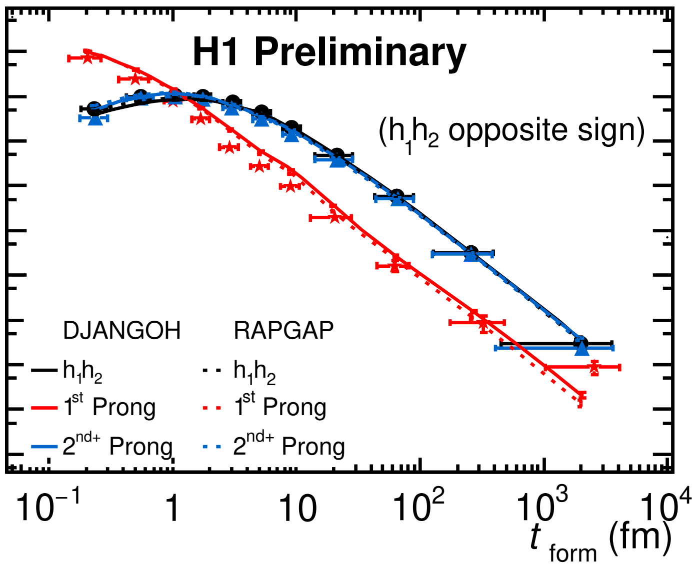
Difference in flavor combinations

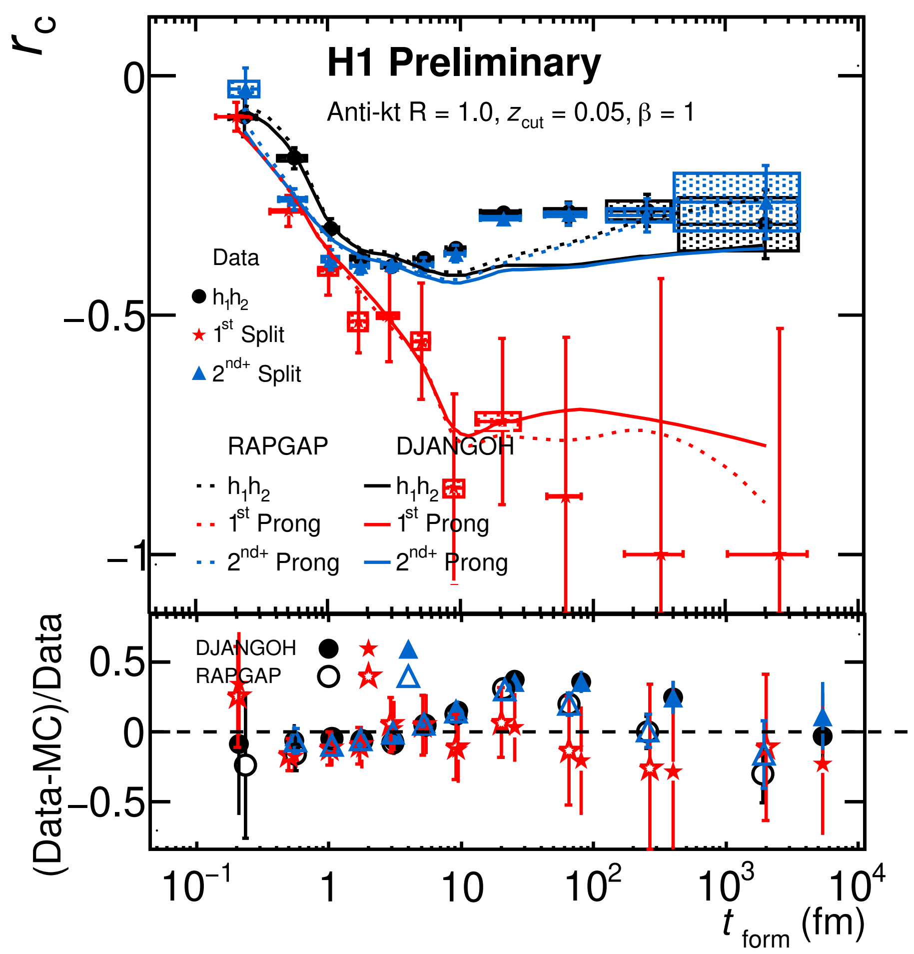


- Correlations are much stronger for $\pi^-K^\pm$ than for $\pi^+K^\pm$ in PYTHIA
- As p_T increases $\pi^+K^\pm$ correlations weakens whereas $\pi^-K^\pm$ strengthens
- Significant difference between PYTHIA and Herwig

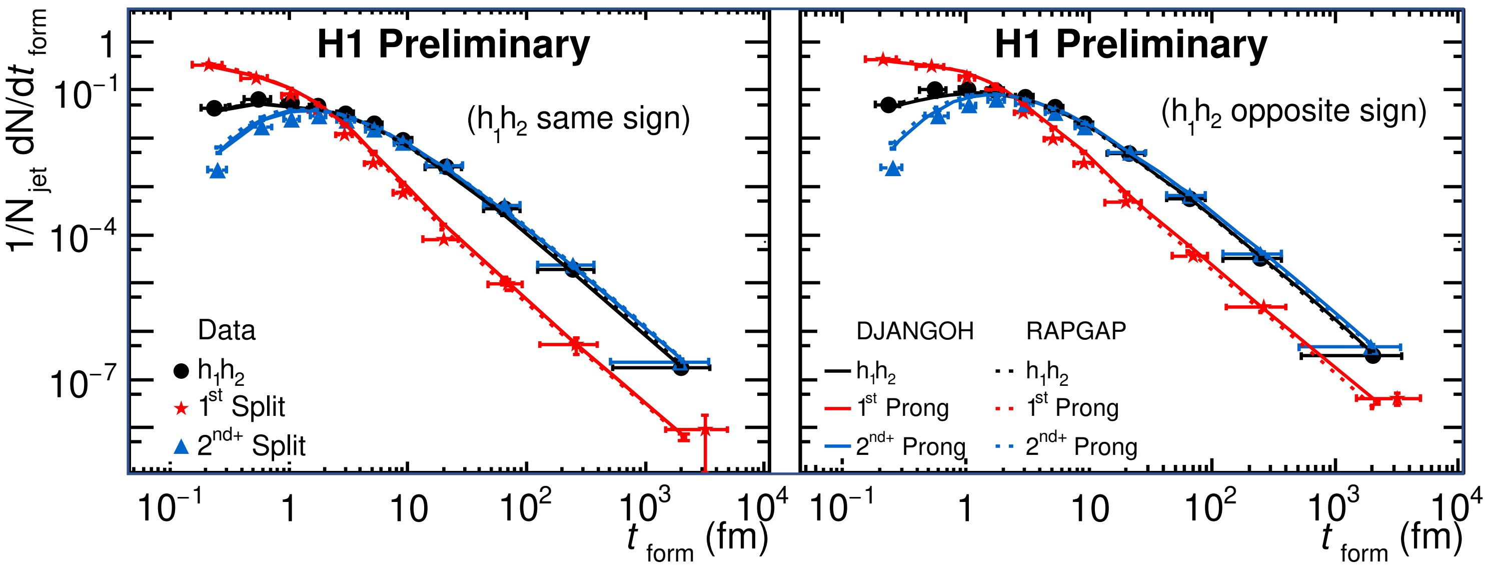
r_c with formation time ($z_{cut} = 0.05$)

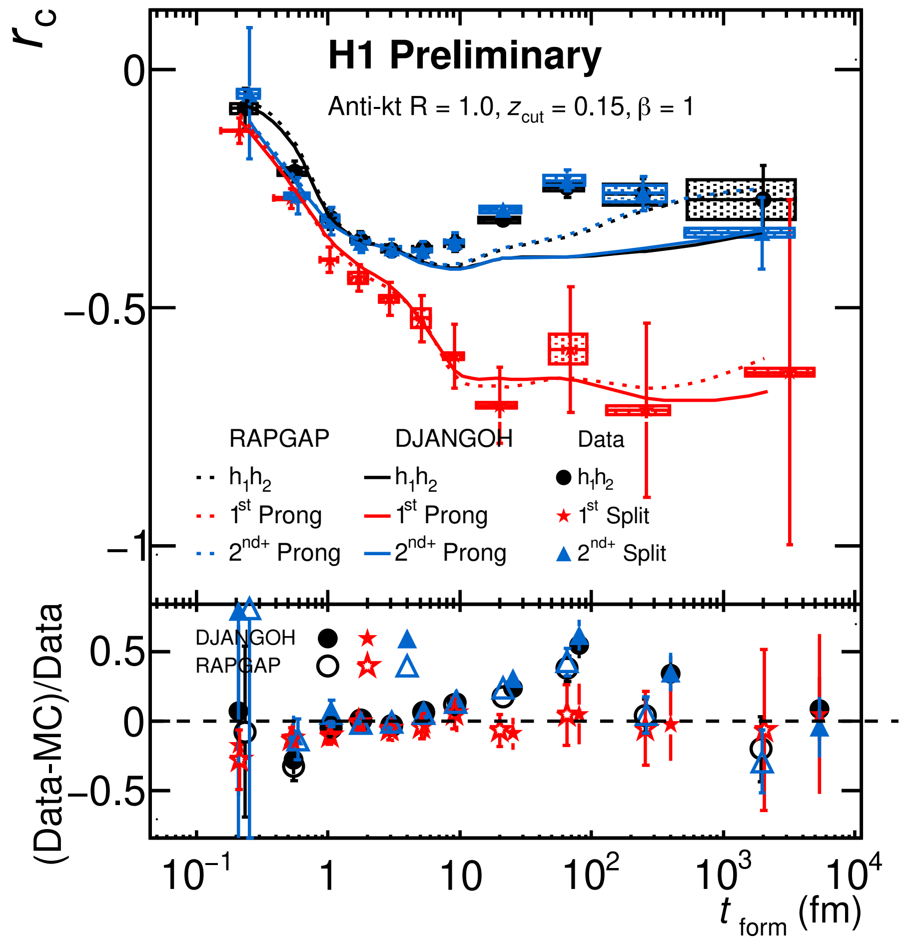




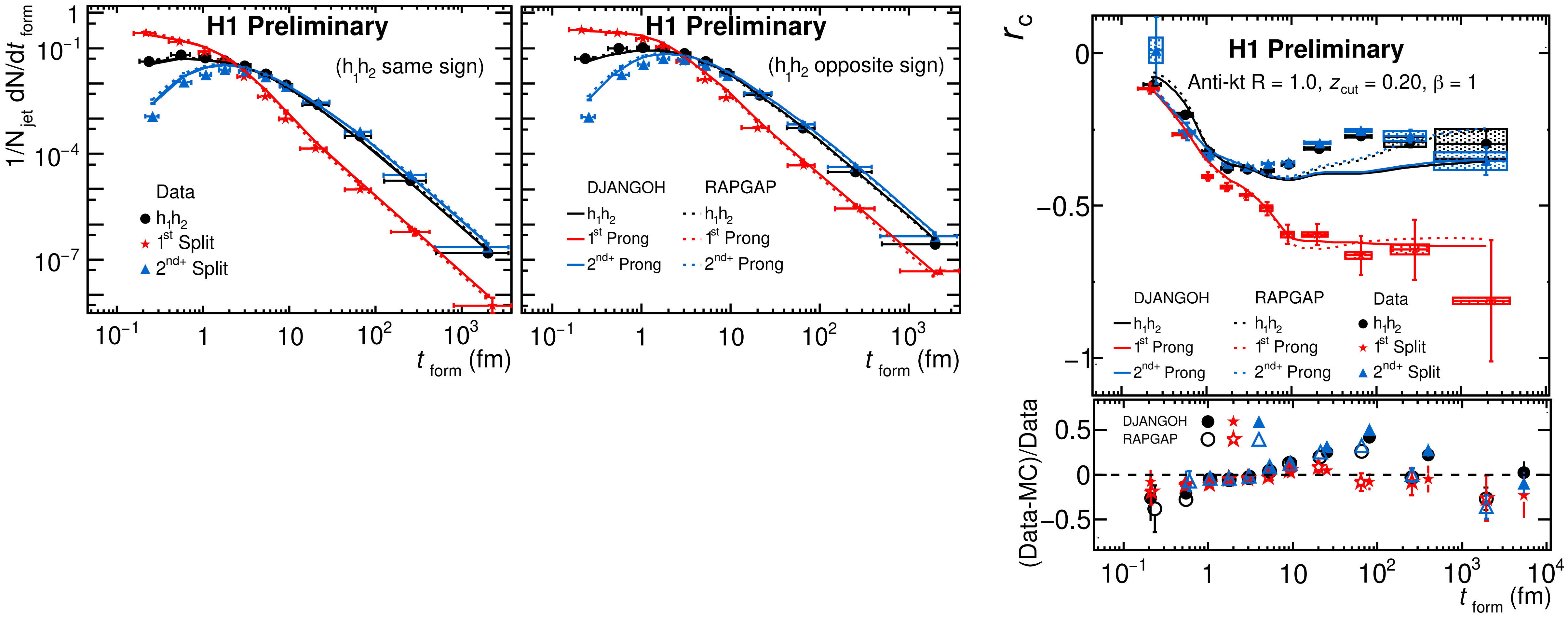


r_c with formation time ($z_{cut} = 0.15$)

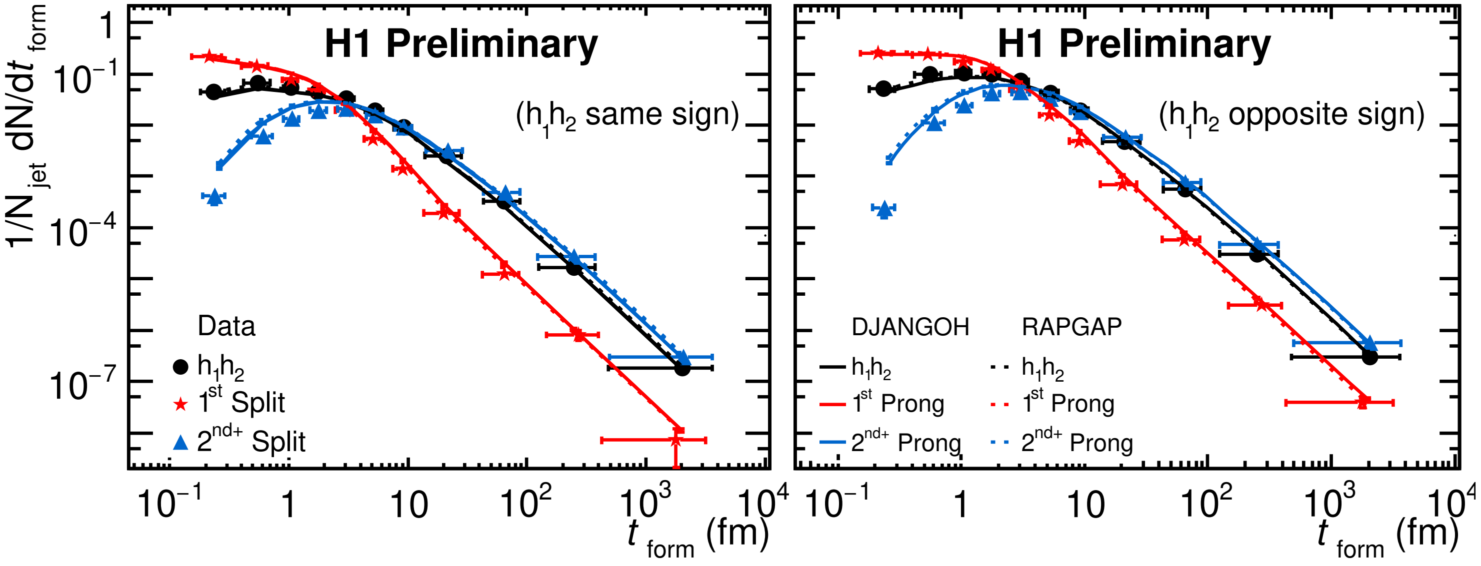


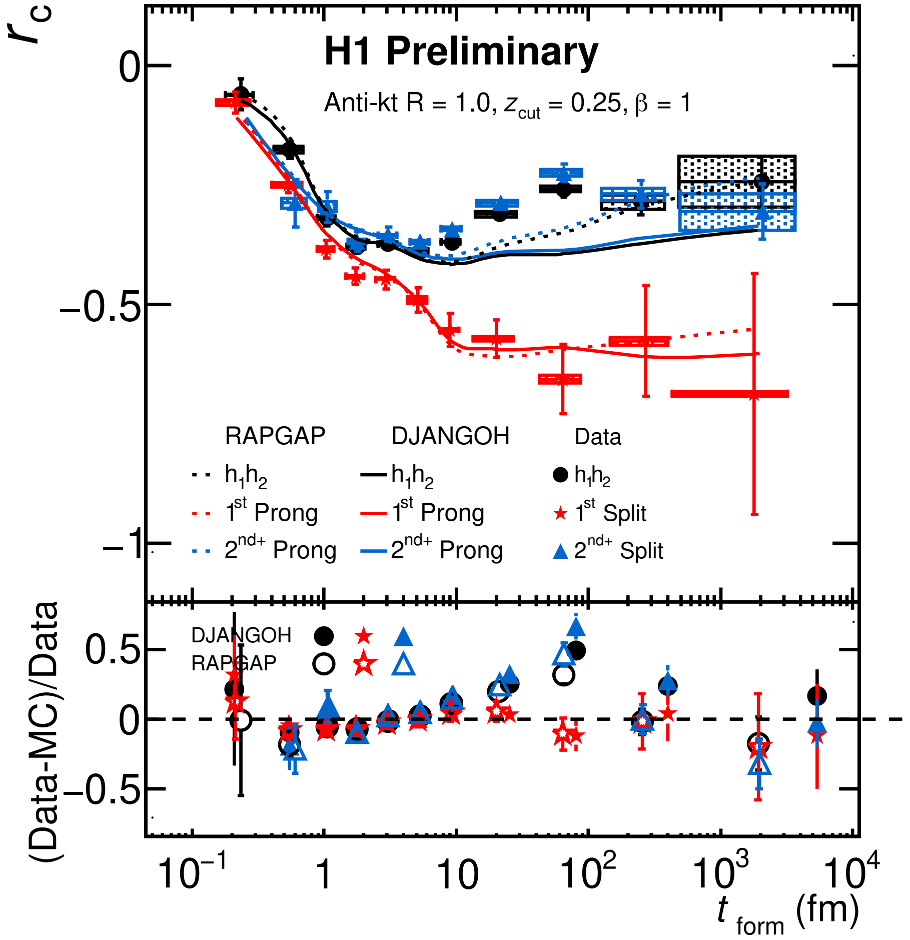


r_c with formation time ($z_{cut} = 0.20$)



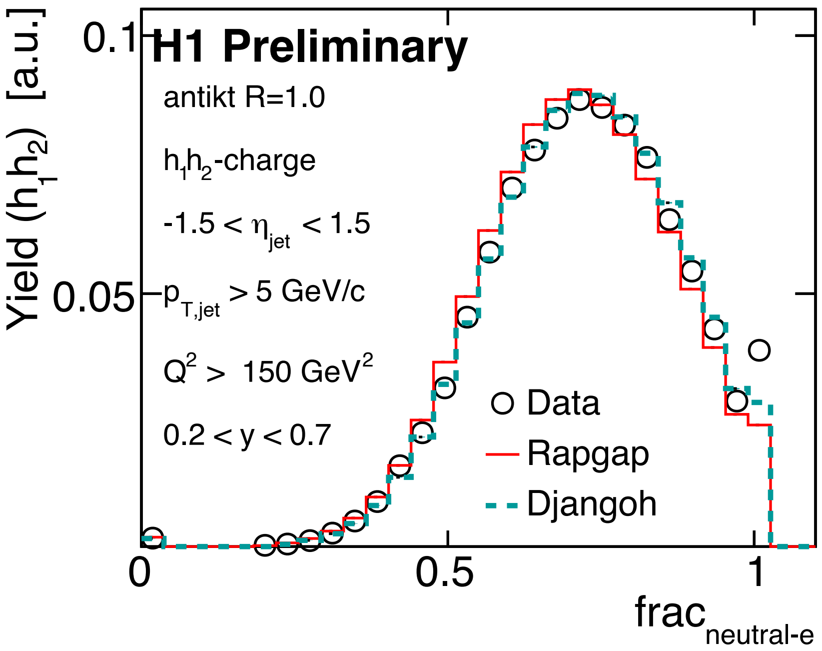
r_c with formation time ($z_{cut} = 0.25$)



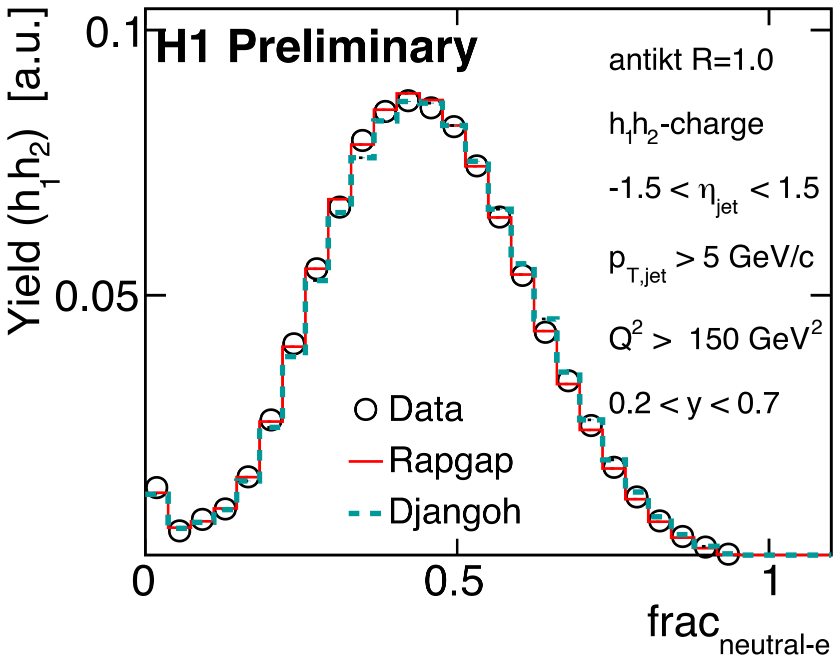


Neutral energy fraction

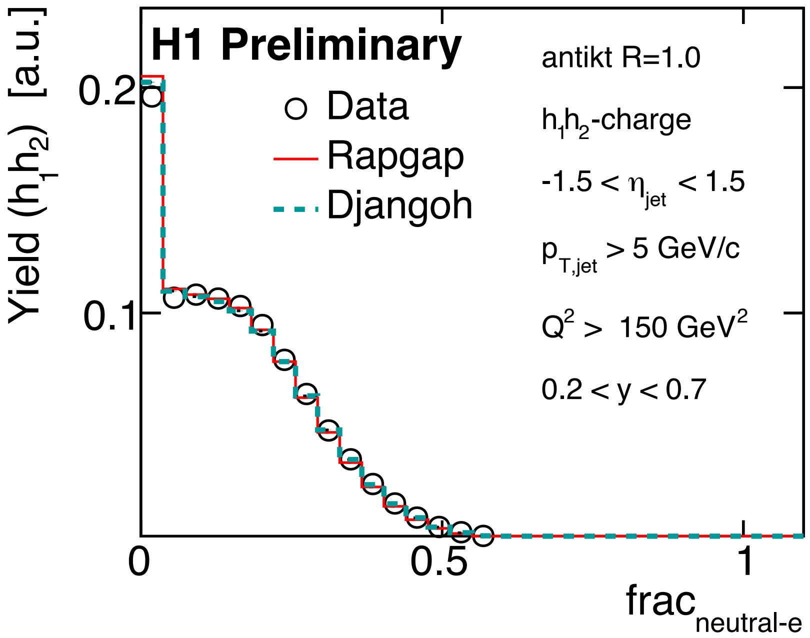
neutal lead REC



one charge Jets REC



two charge REC



z for subjets at prongs